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DYNAMIC STRAIN WAVES - A DEVELOPMENT PERSPECTIVE

R. HASENBEIN

B. ARTUS

A. GABRIELE

G. CUNNINGHAM

D. FINLAYSON

R. GAST

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US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

CLOSE COMBAT ARMAMENTS CENTER

BENÉT LABORATORIES

WATERVLIET, N.Y. 12189-4050

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A discussion of dynamic strain waves in large caliber cannon tubes and an extensive analytical treatment of this phenomenon was previously presented at the Fifth U.S. Army Symposium on Gun Dynamics.

This report considers the implications these dynamic strains had on the development of a particular cannon tube, including measurement techniques which evolved during tests at the proving ground, predictive design methods

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INTRODUCTION

A discussion of dynamic strain waves in large caliber cannon tubes and an extensive analytical treatment of this phenomenon was previously presented at the Fifth U.S. Army Symposium on Gun Dynamics (ref 1).

This report considers the implications these dynamic strains had on the development of a particular cannon tube, including measurement techniques which evolved during tests at the proving ground, predictive design methods which have since become standard analytical tools, and potential problems which have been identified for future study.

BACKGROUND

The 120-mm M256 cannon is the main weapon of the U.S. M1A1 Abrams Tank. This cannon was originally designed and developed by Rheinmetall in the Federal Republic of Germany, and it ranks among the most powerful tank weapons in the world. However, since its adoption by the U.S. Army into the Abrams Tank System, the armor on threat tanks has become increasingly more formidable; therefore, considerable interest existed in the mid-1980s in "upgunning" the M256 cannon simply by increasing the length of its tube (i.e., increasing its length of projectile travel in order to achieve higher muzzle velocity). The experimental tube that was envisioned to accomplish this was designated the 120-mm XM25 tube. System planners indicated a desire to make an absolute minimum of other changes to the Abrams Tank to achieve this increased firepower capability.

When the M256 cannon was integrated into the M1A1 Tank, it was a relatively easy task to balance this gun about its trunnions. This was deemed desirable since it simplified the weapon stabilization problem. However, when the tube

was extended to XM25 length using wall thicknesses similar to those in the M256 tube, designers found that a considerable imbalance resulted. For a new system design, this problem could be addressed by several methods such as the use of equilibrators, counterweights, or enhancements to the elevation/stabilization system. However, since the system guidance indicated a desire to make minimum changes to the existing M1A1 Abrams Tank, tube designers were left with the primary responsibility for minimizing the imbalance. It was quickly realized that, in the design of this conventional all-steel tube, the only method of accomplishing this was to reduce wall thicknesses towards the muzzle end to values less than the previous design practice might have deemed judicious. System planners, however, indicated that the higher risk of doing so would be acceptable for this experimental tube and urged that this approach be taken.

As expected, when the wall thicknesses towards the muzzle end of the XM25 tube were decreased, calculated stresses and strains increased since there was less material to contain the same amount of pressure. While it appeared that these values would be acceptable from a single-shot strength viewpoint, concern arose that the critical fatigue zone in the tube might shift from the chamber area to the muzzle. As a result, fracture mechanics and fatigue experts in Benet's Research Division were consulted, and they made appropriate recommendations for laboratory testing in the forward tube sections. At the same time, however, they warned that significantly reducing tube wall thicknesses near the muzzle could result in unknown end effects and loading patterns which might increase strains beyond those that might otherwise be predicted. Their considered advice that the muzzle end of the tube be studied intensively during engineering tests began the process which led to the later identification of the dynamic strain phenomenon.

PROVING GROUND TEST METHODOLOGY

The 120-mm XM25 tube (Figure 1) was subsequently designed with wall thicknesses towards the muzzle end as low as 12.7 mm; for reference, the minimum wall thickness of the M256 tube is 17.0 mm (one-third greater). After the tube was fabricated by the Watervliet Arsenal (NY), it was shipped to Aberdeen Proving Ground (APG) (MD) for engineering tests under the direction of the Combat Systems Test Activity (CSTA). Test plans requested that multiple strain gages (oriented both circumferentially and longitudinally) be placed at several axial locations on the tube from the bore evacuator to the muzzle and that available DM13 APFSDS-T cartridges be utilized when firing. During the initial stages of the test, considerable difficulty was encountered simply keeping the gages attached to the tube, particularly those located towards the muzzle. After a period of experimentation by CSTA, however, a satisfactory application procedure was determined (shown schematically in Figure 2). Subsequent results obtained when firing the DM13 cartridge produced "strain versus time" traces (an example is shown in Figure 3) that contained what appeared to be anomalies. For example, severe peaks were present in the strain signals well beyond those which would be predicted using equations of statics. Further, significant compressive circumferential strains were observed as the projectile approached the strain gage locations. And finally, longitudinal strain gage results generally oscillated about "zero strain," but at amplitudes which approached those of the circumferential strain gages.

Two significant observations were made at this early juncture of the test. First, it was noted that when firing the high speed DM13 round, the lack of agreement between observed peak strains and calculated strains decreased significantly in the rearward gage locations where projectile velocity is lower.

Second, when a lower velocity M831 HEAT-TP cartridge was fired (grateful acknowledgement should be given to Mr. Clyde Musick, CSTA Test Director, for this suggestion), there was much better agreement between predicted and experimental results at all gage locations. These two observations led designers to plot "strain amplification (defined as 'peak strains measured by the gages divided by calculated static strain') versus projectile velocity" (at that gage location) for the two different cartridges. The resulting curve seemed somewhat well-behaved, the ratio being approximately 1.1 at lower velocities and increasing monotonically to approximately 4 as projectile velocity increased. This provided the first clue that the phenomenon might be somehow related to projectile velocity.

Dynamicists in Benet's Research Division were asked to consider whether the observed data were the result of an actual physical phenomenon or simply an instrumentation problem. Their subsequent closed-form analytical efforts (which were presented at the Fifth U.S. Army Symposium on Gun Dynamics (ref 1)) revealed that the phenomenon being observed was indeed real, and they provided significant insights into its nature. Disturbingly, however, the proving ground strain traces (Figure 3) did not bear a resemblance to those predicted by the Benet researchers. After looking closely at the predicted analytical strain waves and considering the strain measuring methodology at the proving grounds, Benet researchers were able to propose two significant modifications to the latter:

- First, it was suggested that the filters being used during recording of the strain signals (10 kHz lowpass) be increased to a higher value (30 kHz lowpass), since the anticipated frequencies of the strain wave should be on the order of 15 kHz;

• Second, it was suggested that the time "window" for presentation of individual strain traces be decreased from the previous 100 milliseconds to around 5 to 10 milliseconds in order to better observe details of the wavelike nature of the strains. The time "window" should be the same for all strain gages on the entire tube for a given round:

- beginning slightly before the projectile arrives at the rearmost strain gage, and
- ending slightly after the projectile exits the tube.

The above suggestions were incorporated into the CSTA/APG firing tests, and the benefits were immediately apparent. Good correlation was noted between the analytically-predicted dynamic strain traces and those obtained from firing tests (Figure 4), including frequencies and amplitude. Moreover, specific events such as projectile passage, projectile exit from the tube, and predicted static strain could be superposed on the traces to assist with the data reduction (Figure 5).

Since that time, several additional "rules of thumb" have evolved for the conduct of dynamic strain tests at proving grounds. Best results are obtained when the test includes a wide variety of cartridge types, ranging from the slowest of those which will be fired from the tube in actual service (or training) to the fastest. In some cases it may be desirable to pre-condition the cartridge to elevated temperatures to attain the highest possible muzzle velocities. Generally, five (minimum) to ten (preferred) rounds of each type should be fired. Strain gages should be applied at several axial locations on the tube, taking care to select positions which include lower projectile velocities (e.g., slightly forward of mid-tube) as well as higher velocities towards the muzzle. Five to six axial positions are currently selected, depending on

the number of available channels for recording data at the proving ground. At each of these locations, four circumferential strain gages should be attached as shown in Figure 2, taking care to locate them at precisely the same axial position. Longitudinal gages may also be used, but these are often of less general interest and are more difficult to interpret.

In reducing dynamic strain data, the following procedure is now generally used:

- Determine the peak strain value at the time associated with projectile passage for each strain gage. In order to select the correct peak, projectile in-bore location must be known or estimated. This is done with the greatest accuracy if projectile muzzle velocity is concurrently measured during the dynamic strain test and later used to refine interior ballistic model predictions.

- In reporting the peak dynamic strain at a given axial location for any individual round fired, it is statistically best to use the average of the peak values indicated by all four strain gages. This tends to cancel out the additional strains which might be added/subtracted by bore eccentricity and axial tube flexure.

- Dynamic strain values are most simply portrayed by plotting "peak strain versus tube axial location" for each cartridge type and pre-conditioning temperature (see example in Figure 6). It is often instructive to also show the calculated static strain on the same graph. Note in Figure 6 that the results of each round are shown, producing a (real) array of possible results. Mean values (for later comparison with analytical predictions) and standard deviations (which increase significantly towards the muzzle) are also often calculated for the entire group of five to ten rounds and displayed on a similar graph.

• Also of interest are plots of "dynamic strain amplification versus tube axial position" for each cartridge type and pre-conditioning temperature. Again, strain amplification is defined as the peak dynamic strain divided by the calculated static strain at that location and pressure. Figure 7 shows an example of this type of plot, and it is based on the mean dynamic strain value at each of the axial locations.

• A significant additional output of a dynamic strain test is a plot of "dynamic strain amplifications versus projectile velocity." One benefit of this type of curve is that the results from all cartridge types and pre-conditioning temperatures may be combined into one figure. The disadvantage, of course, is that projectile velocities are often classified, thereby limiting the opportunities for presentation of these types of results.

FINITE ELEMENT ANALYSIS

Apart from understanding the phenomenon of dynamic strains and being able to test for them, it is important for tube designers to have at their disposal techniques for analysis of dynamic strains during the design phases prior to manufacture. The algorithms must be specifically geared towards the actual tube geometry and the array of ammunition (either existing or envisioned) to be fired through it. A satisfactory methodology for doing this has evolved which has two separate steps:

• First, the loading conditions on the tube must be determined, specifically, the applied pressure and the projectile velocity. To accomplish this step, appropriate data are supplied as inputs to an interior ballistics computer code, and output files containing the following information are created (both being functions of time):

- pressure in the bore at the base of the projectile;
- axial location of the projectile.

• Second, the data files generated in the ballistic analysis above are used as inputs into a dynamic finite element analysis (FEA). An axisymmetric gridwork which duplicates the interior and exterior diameters of the cannon tube is created for use with a non-linear finite element code capable of performing dynamic analyses (such as ABAQUS). Although this type of FEA is potentially large in scale, it can be performed in a timely manner using a supercomputer. Results produced using this technique have compared quite favorably with strain gage data from proving ground tests. A typical output graph of "circumferential strain versus time" is shown in Figure 8 and one of "peak dynamic strain versus tube axial position" is shown in Figure 9.

This analytical method can provide additional insights regarding a given tube's dynamic response in areas where actual measurements are either difficult or impossible (for example, at the extreme muzzle of the tube, at the bore, or within the walls of the tube). Outputs can also be used to create video animations which further clarify the physical nature of the dynamic strain waves.

DESIGN IMPLICATIONS OF DYNAMIC STRAINS

There are various implications of dynamic strains on developmental cannon tubes, some of which are reasonably well understood and some of which are excellent candidates for ongoing research. A partial list would include the following items:

- effect on tube strength (failure criteria);
- effect on tube fatigue life (high strain rate loading, multiple strain cycles per round fired);

- effect on projectile behavior due to local clearances or constrictions at tube-projectile interfaces (e.g., initiation of balloting, sabot tip-off, etc.);
- effect on adhesion/cohesion of bore coatings such as chromium plating;
- creation of local accelerations in the tube walls.

It is interesting that the last item on this list, which looks most innocuous, may be of the most immediate concern due to the severe environment which these accelerations create for attached components such as Muzzle Reference System Collimators. Resulting local accelerations near the muzzle can be on the order of ± 100,000 g's and may result in breakage of delicate optical components.

CONCLUSIONS

Dynamic strains are a phenomenon which have only recently been identified and understood. The effort to do so has been the result of an intensive collaboration between research-oriented people, who are fundamentally interested in understanding and explaining physical phenomena, and development-oriented people, who are required to deliver functional hardware in a timely manner. From the development perspective, this problem has been (and continues to be) a prime example of the mutually beneficial relationship that can exist between the two, for truly without the researchers, the dynamic strain problem would never have been observed and understood at all.

(**SPECULATIVE POSTSCRIPT:** It is likely that researchers likewise feel a perverse reciprocal appreciation for developers who create exciting new problems like these in the first place by attempting to expand the limits of hardware performance.)

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XM25

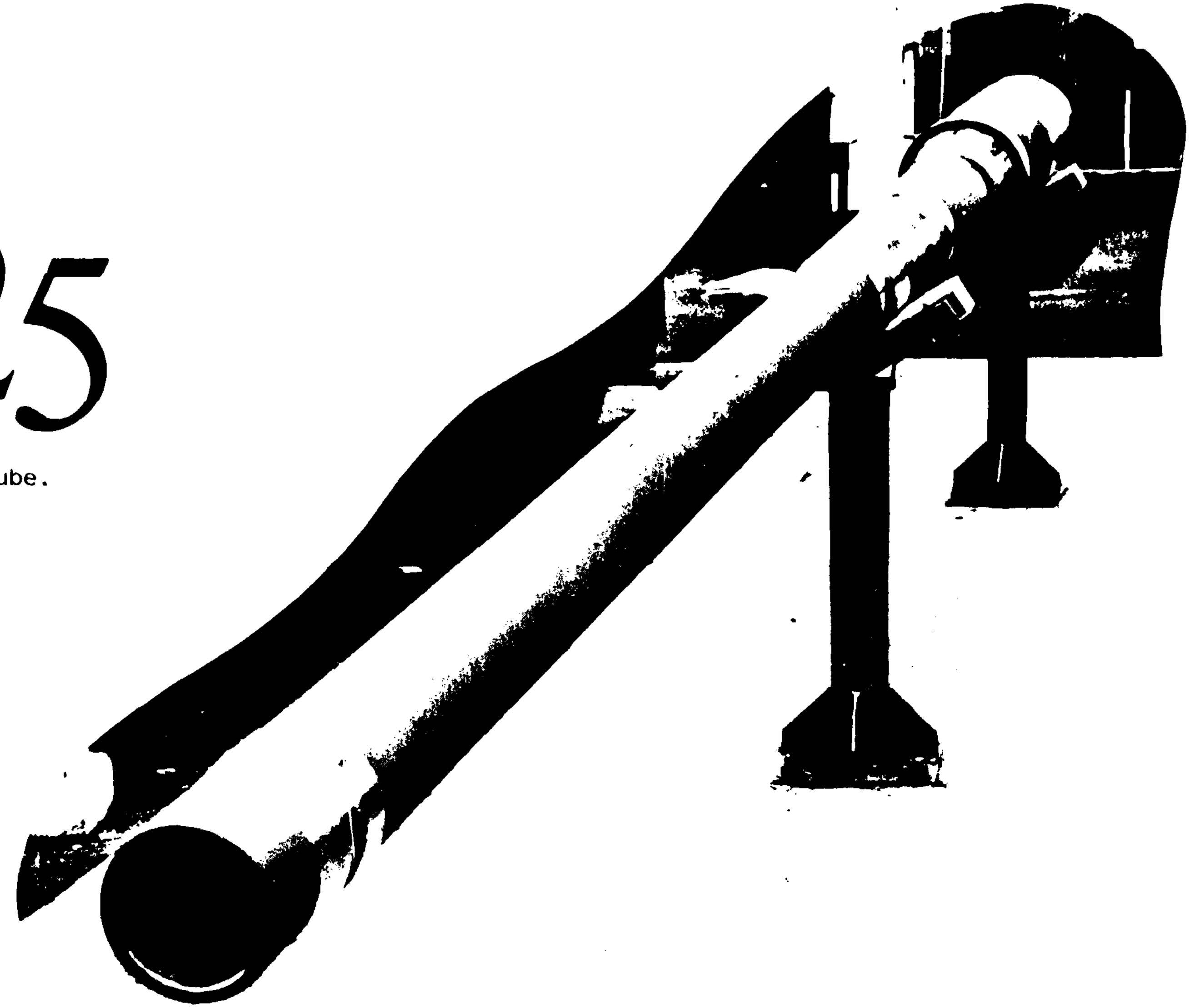
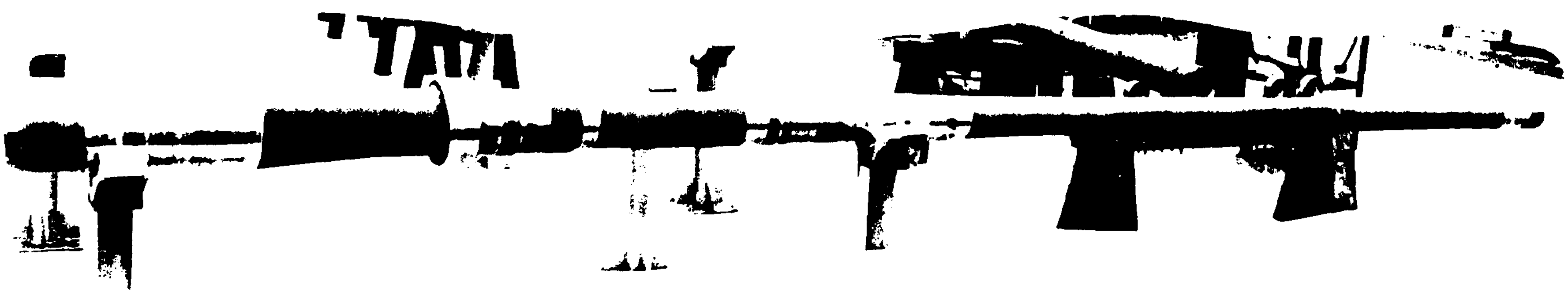
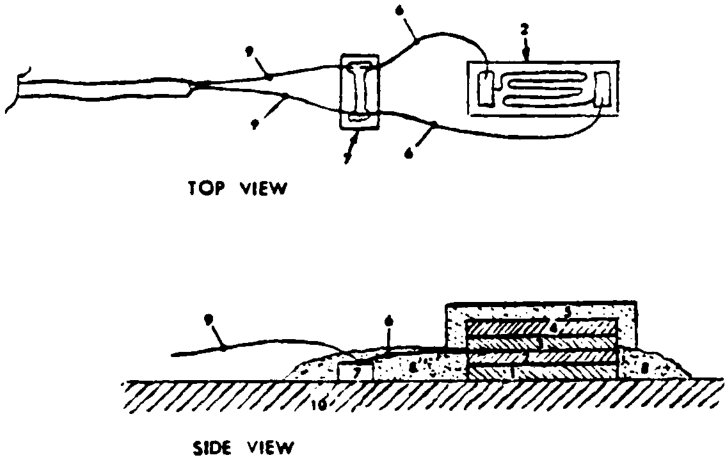


Figure 1. 120-mm XM25 tube.





1. M-BOND 610
2. MICROMEASUREMENT STRAIN GAGE (EA-06-250BF-350)
3. RUBBER PAD
4. FOAM RUBBER SPONGE
5. GUN TAPE
6. SINGLE STRAND OF WIRE
7. TABSTRIP
8. M-COAT
9. WIRE FROM CABLE
10. CANNON TUBE

Figure 2. Strain gage application to tube.

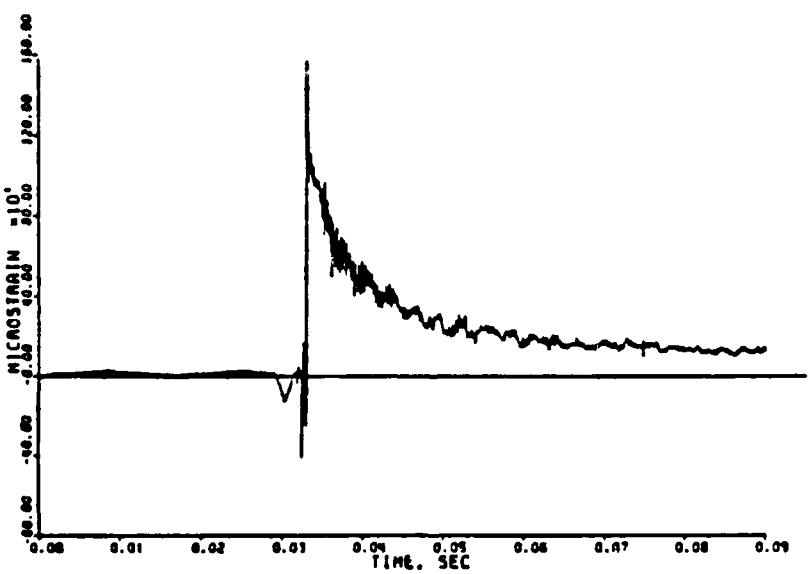


Figure 3. Initial strain versus time trace.

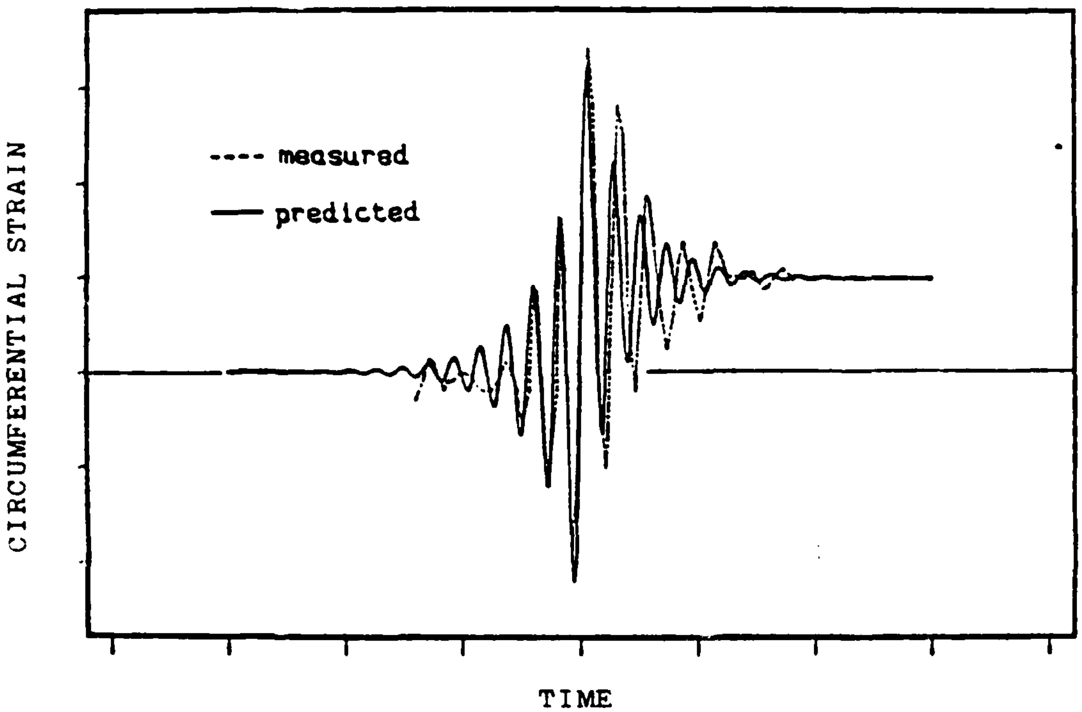


Figure 4. Correlation between strain traces (analytical versus experimental).

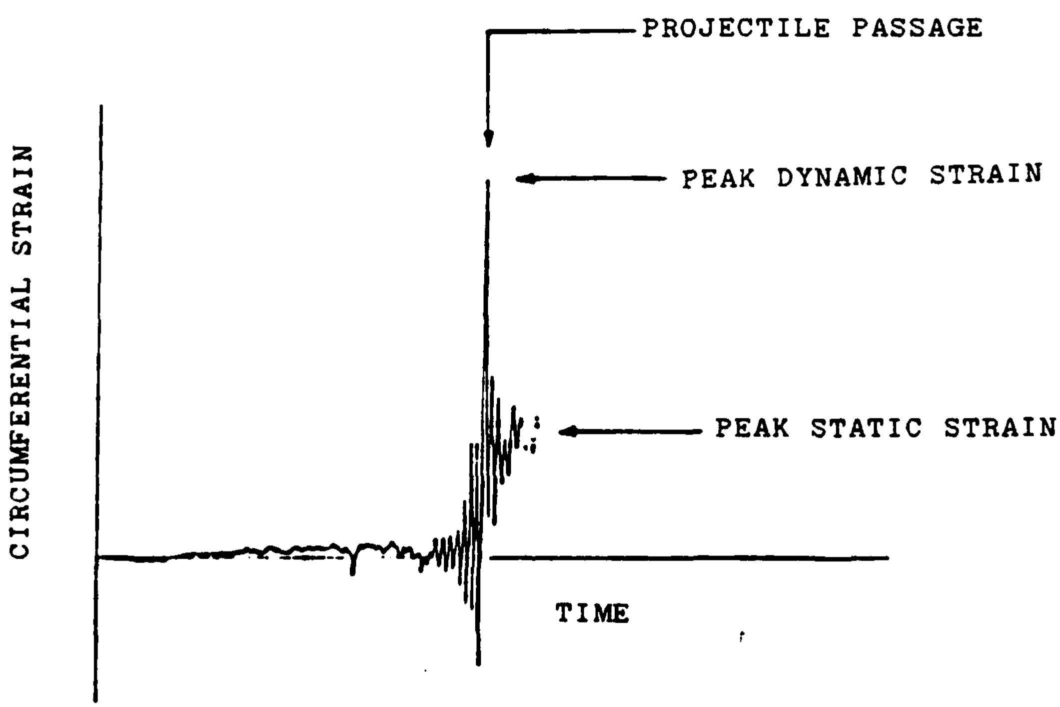


Figure 5. Dynamic strain trace with event markers.

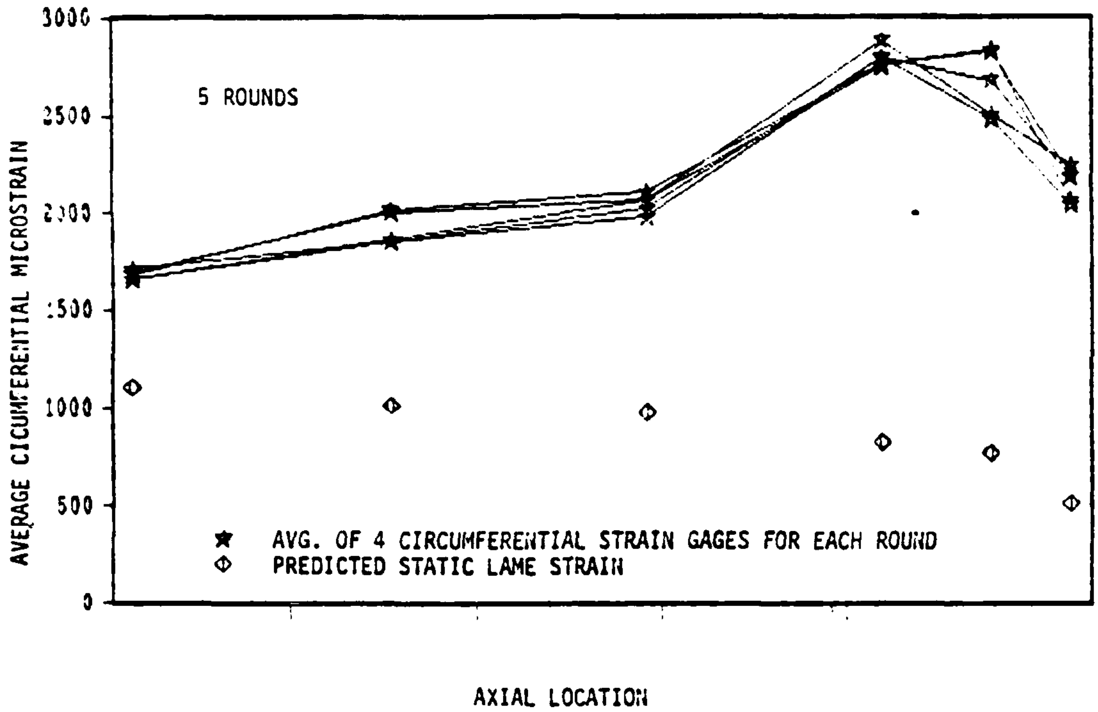


Figure 6. Typical graph of "peak dynamic strain versus tube axial position."

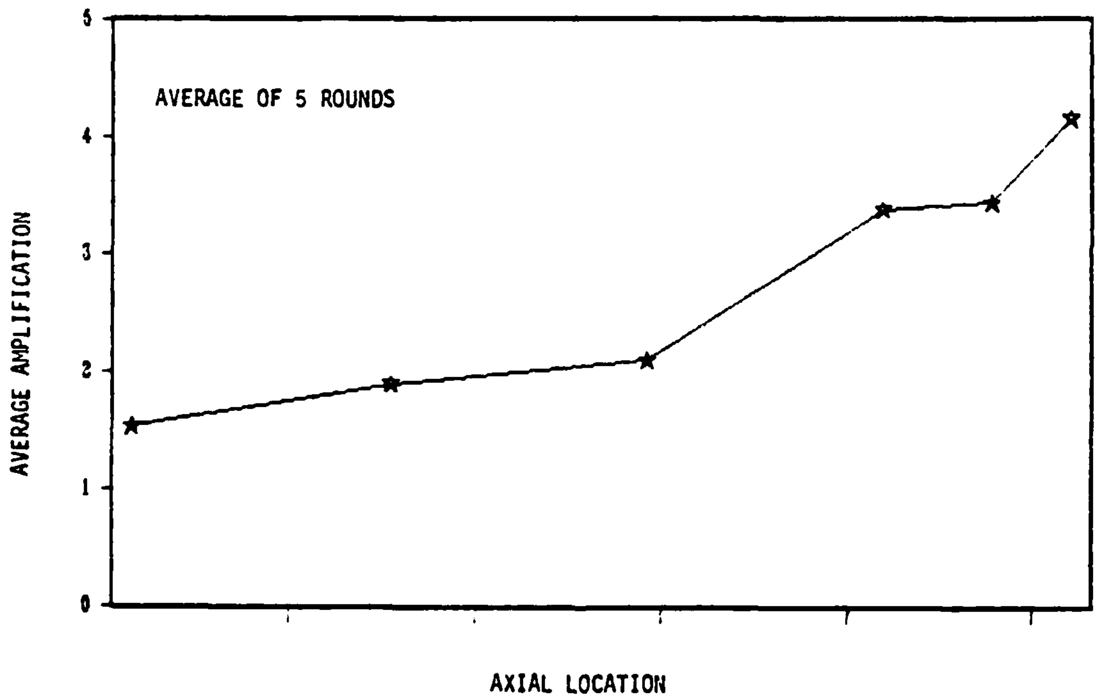


Figure 7. Typical graph of "dynamic strain amplification versus tube axial position."

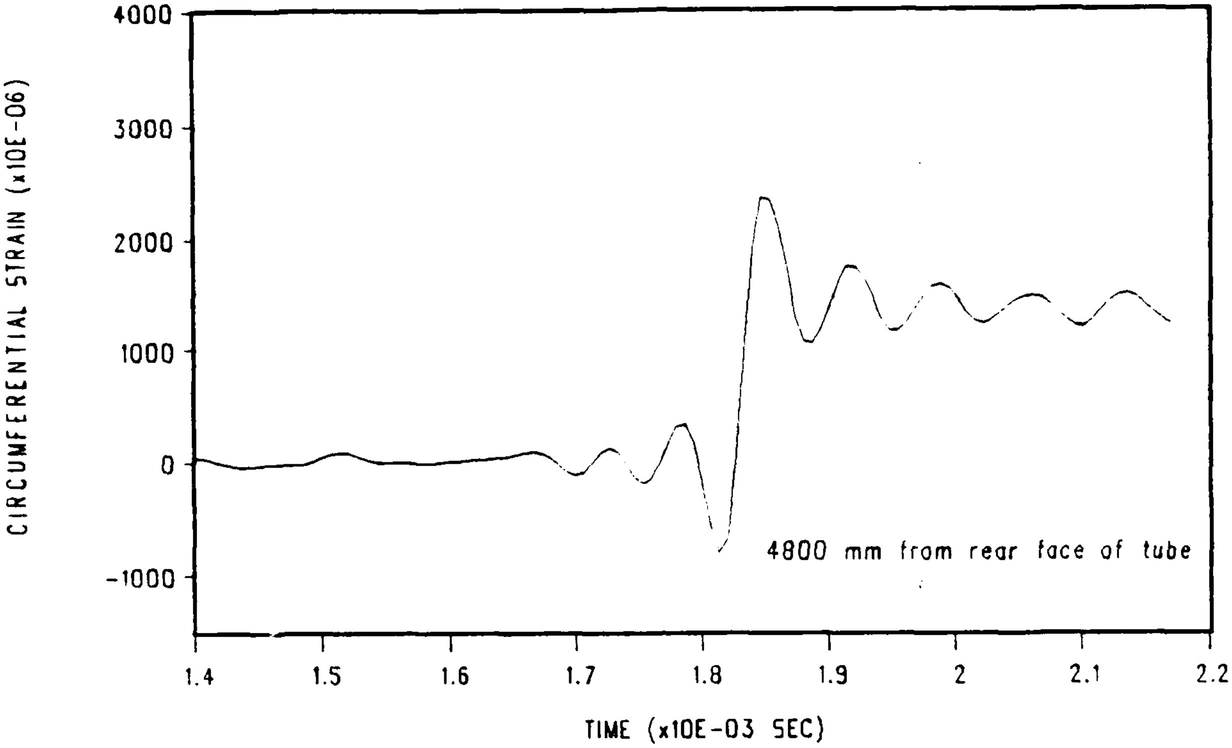


Figure 8. Typical "circumferential strain versus time" curve from dynamic finite element analysis.

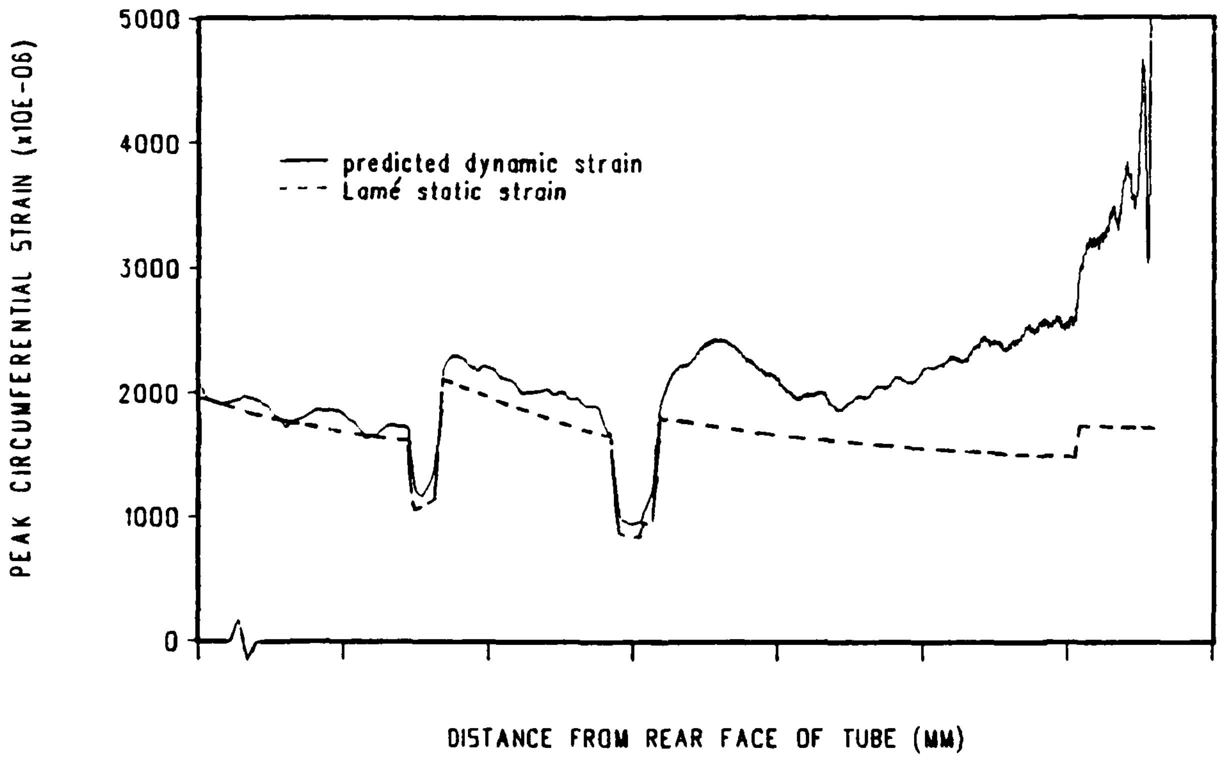


Figure 9. Typical "peak dynamic strain versus tube axial position" curve from dynamic finite element analysis.

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